SOLID-STATE POWER SWITCHES FOR HPM MODULATORS

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Abstract

Power modulators for pulsed microwave applications, generally utilizing a thyratron-switched PFN, typically produce 50-120 kV, 1-2 kA microsecond timescale pulses with sub-microsecond (~100-200 nsec) risetimes. This paper will review an investigation into the feasibility of utilizing certain solid-state power switches at the relatively fast speeds required for HPM modulators. Two very different thyristor switches, an ABB HCT and an n-type MCT, were investigated in a fast (~136 nsec), low-impedance 1.4-μsec PFN. Limited success was obtained, as both switches demonstrated sub-microsecond switching times. The ABB HCT switched a bias of 3840V with a risetime of 524 nsec. The N-MCT was faster, switching a bias of 944V in 220 nsec. These results indicate that thyristor switches may be fast enough for some HPM modulator applications.

Introduction

Modulators required to drive high-power microwave (HPM) sources, such as magnetrons and vircators, typically must generate short (~microsecond) high-voltage (~50-100 kV) pulses for repetitive operation at kilohertz repetition rates. At present, the hydrogen thyratron is the only switch capable of meeting the simultaneous requirements of high-voltage, high repetition, short pulse operation. These switches are large, expensive and require substantial auxiliary electronics for triggering and for the cathode and hydrogen reservoir heaters (heater currents of ~100 Amperes are typical). This auxiliary (or "housekeeping") equipment is of substantial size and weight and consumes a significant amount of power, several kilowatts being typical. Also, some thyratron designs must be immersed in dielectric oil for cooling and high-voltage insulation. While some progress has been made in thyratron engineering, especially in the area of air-insulated thyratrons, the use of thyratrons in tactically-feasible modulators is severely limited by the size and weight of the device itself and its associated auxiliary equipment. Despite its disadvantages, the thyratron remains the only viable switch for many HPM applications.

Recent advances in semiconductor technology suggest that a solid-state alternative to the thyratron should be considered for HPM modulators. Thyristor structure devices, such as silicon-

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14. ABSTRACT
Power modulators for pulsed microwave applications, generally utilizing a thyratron-switched PFN, typically produce 50-120 kV, 1-2 kA microsecond timescale pulses with sub-microsecond (-100-200 nsec) risetimes. This paper will review an investigation into the feasibility of utilizing certain solid-state power switches at the relatively fast speeds required for HPM modulators. Two very different thyristor switches, an ABB HCT and ann-type MCT, were investigated in a fast (-136 nsec), low-impedance 1.4-~sec PFN. Limited success was obtained, as both switches demonstrated sub-microsecond switching times. The ABB HCT switched a bias of 3840V with a risetime of 524 nsec. The N-MCT was faster, switching a bias of 944V in 220 nsec. These results indicate that thyristor switches may be fast enough for some HPM modulator applications.

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controlled rectifiers (SCRs), long used in utility applications, have been evaluated at Army Research Laboratory for high-energy pulse-switching capabilities[1] and elsewhere for their high-di/dt switching[2]. The results indicate that thyristors are possible candidates to replace the thyratron for many applications. The main advantages are compactness, minimal housekeeping equipment and power, increased repetition rate, instant start capability, and reliability. The main drawback is the need for series and parallel operation of solid-state switches to achieve the high voltages and currents required for many HPM applications.

ARL began a feasibility study to investigate solid-state switches for pulsed, HPM applications. This was an initial effort, aimed at establishing a testbed for HPM solid-state switch study as an extension of our already successful solid-state switch for electric gun program and our thyratron-based HPM effort. This initial program was sponsored by Air Force Phillips Laboratory. This paper reviews the status of this effort to date with an evaluation of two promising candidate switches for HPM modulators.

Candidate Switches

Two candidate switches were identified in our preliminary study. These devices are the N-type MOS Controlled Thyristor (MCT) and the High Current Thyristor (HCT). These are *pnpn*-type, three terminal devices, with an anode, cathode, and gate electrode. A trigger pulse applied to the gate turns the device on or off. These devices are all based on the use of a highly interdigitated gate structure or equivalent to turn on the entire device, thus reducing the time delay for plasma spread, and thereby achieve very high di/dts, on the order of 10's of thousands of amperes per microsecond. While these devices were designed for longer pulse, utility and power control applications, their advanced gate structures could make them suitable for short-pulse switching applications. We have already investigated some of the pulse switching characteristics of related devices, such as the P-type MCT and SCRs, for electric gun and power conditioning applications and these related device tests indicate the N-type MCT and HCT are good candidates for HPM modulators.

The MCT developed by General Electric and Harris Corporation is a new class of thyristor which can be closed or opened with control signals and control energies equivalent to those required to charge and discharge the gate capacitance of a power MOSFET. The device can be thought of as a converted thyristor in which the resistance of the emitter shorts is controllable by means of an highly-interdigitated MOS gate structure. The resulting device has the power handling capability and low conduction loss of a thyristor combined with the ability to be turned on and off with microwatts of gate power. The N-MCT version is the fastest version and has the lowest switching losses. We currently have a stock of experimental N-MCTs with a voltage rating of 1200 V, di/dt capability of 10 kA/µs, and an average current capability of 35A. The device has a die area of 0.4 cm^2 and is mounted in To-218 package. These devices can be easily stacked in a compact array for high-voltage operation. Parallel operation of MCTs has been previously demonstrated[3] and two MCTs in parallel should provide a di/dt of 20 kA/µsec.

The HCT is currently available from ABB. The gate structure is highly interdigitated and is similar to the gate structure of a Gate Turn-Off Thyristor (GTO). It is optimized to provide for fast turn-on. The drive requirements are in the order of milliwatts. Recently developed samples of the HCT 603-45A01 were obtained for this evaluation. These devices are rated for hold-off voltage of 4500 V, a di/dt of 20 kA/µsec, a surge current of 18 kA, and an average current of several hundred amperes. The silicon die is 34 mm in diameter, and the package is 58 mm in diameter with a height of 26 mm. The total weight is 0.3 kg.

Switch Evaluation Testbed

As the goal of this study was to investigate the suitability of the candidate switches for HPM modulator applications, a testbed was required which mimicked the pulse requirements of such modulators. Typical parameters for an HPM modulator are:

Table I. Typical HPM Modulator Parameters

PFN charge voltage	=	50-120 kilovolts
peak current to load	=	~2 kiloamperes
pulse repetition rate	=	1 kilohertz
pulse width	=	~ 1 microsecond
pulse rise time	=	~ 1/10 pulsewidth
load impedance	=	50-100 Ohms

The primary objective of this phase was to determine if the candidate switches had sufficient di/dt capability, ~20 kA/μsec, to handle these relatively fast pulse requirements. As the speed of individual devices was to measured first, before any parallel or series operation was attempted, the PFN charge voltage was limited due to the low voltage hold-off of individual solid-state switches (< 5 kV). It would not be possible to obtain high enough peak currents to determine the di/dt capability of the switches using a high-impedance, 50-100 Ω network at these lower voltages. For high current measurements, a low-impedance PFN was desired.

A network with a 1/2-Ω characteristic impedance was used for these tests. A 5-section, E-type PFN with a designed characteristic pulse width of 1.1 μsec was constructed based on NWL capacitors. These are 20-kV, 0.1 μF units rated for kHz pulsed operation. Each section consists of two of these capacitors in parallel for a section capacitance of 0.2 μF. The requisite section inductance is 50 nH. This small section inductance is provided by the copper strap connecting capacitive sections. The design circuit risetime, L/R, is 100 nsec. To insure that the intrinsic switch risetime is measured without circuit effects, the connections between the switch, the load, and the PFN must be very low-inductance. The switch is connected directly to a matched 1/2-Ω load consisting low-inductance Carborundum disc resistors, and the complete switch/load assembly is surrounded by a quasi-coaxial housing. This provides a measure of flux cancellation during switching, minimizing circuit inductance. The circuit is shown schematically in Fig.1 and a photograph of the testbed is shown in Fig. 2

To verify the test circuit parameters, the PFN was switched using a "razor-edge" test switch. A test load current waveform is shown in Fig. 3. The pulse displays a 10%-90% risetime of ~136 nsec, indicating the circuit is capable of high-speed. The pulse shape displays some overshoot and droop, but is adequate for these tests. The measured pulsewidth is ~1.4 μsec.

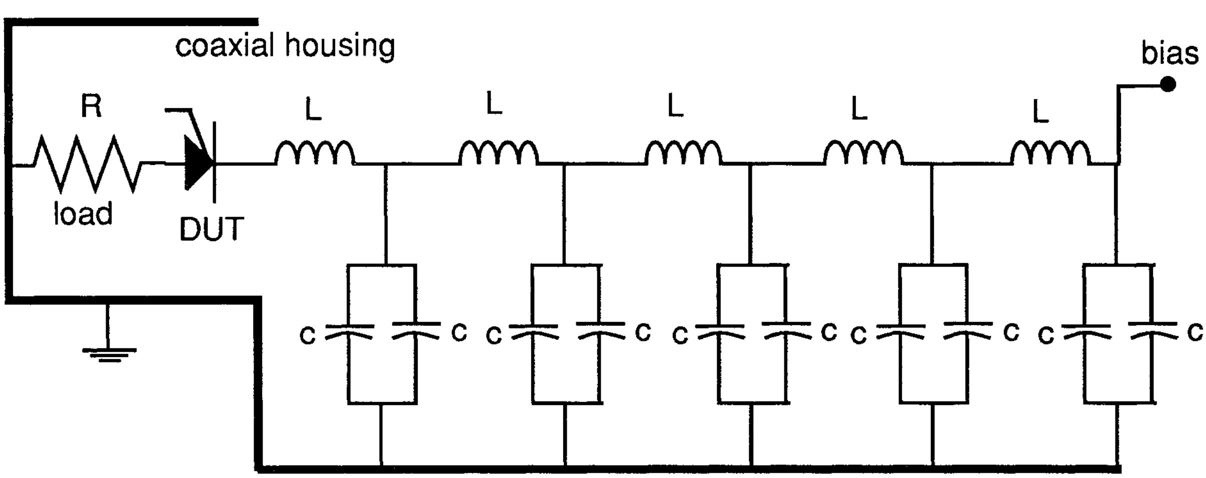
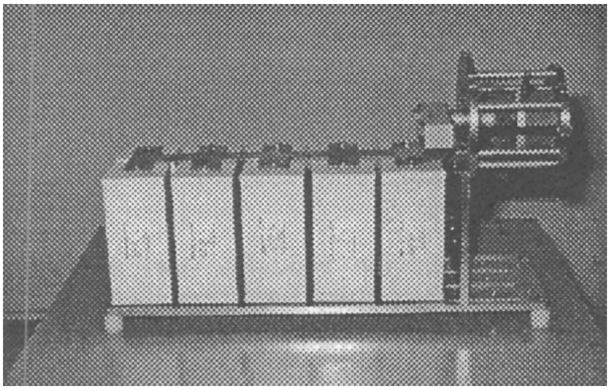


Figure 1 Circuit schematic for switch testbed, with 5-section PFN, switch, and load. The circuit parameters are: c = 0.1 μF, L = 50 nH, R =1/2 Ω. The device-under-test and load are enclosed in a quasi-coaxial housing to minimize circuit inductance.



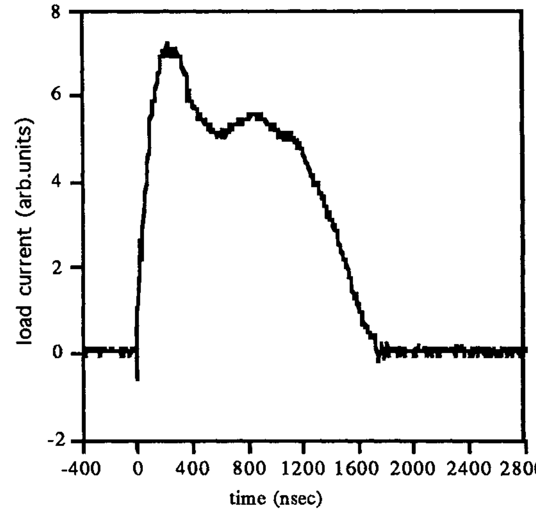


Figure 2. Photograph of switch evaluation testbed.

Figure 3. Representative current pulse from test of PFN, indicating ~136 nsec risetime and 1.4 μsec FWHM pulsewidth.

Switching Data

Individual switches were evaluated in the low-impedance PFN testbed at voltages up to ~75% of their rated voltage. The load current was measured with a Pearson #110 current transformer. Voltage drop across the switch could not be measured due to lack of a fast enough measuring circuit. PRF testing was limited due to trigger generator inadequacies.

A. N-MCT Switching

The N-MCT was tested at anode voltages up to 944V and did prove to be a relatively fast device. Load current waveforms for various bias voltages are shown in Fig.4. The load current pulses are similar in shape to the test pulse of Fig.3, although displaying some inverse current and

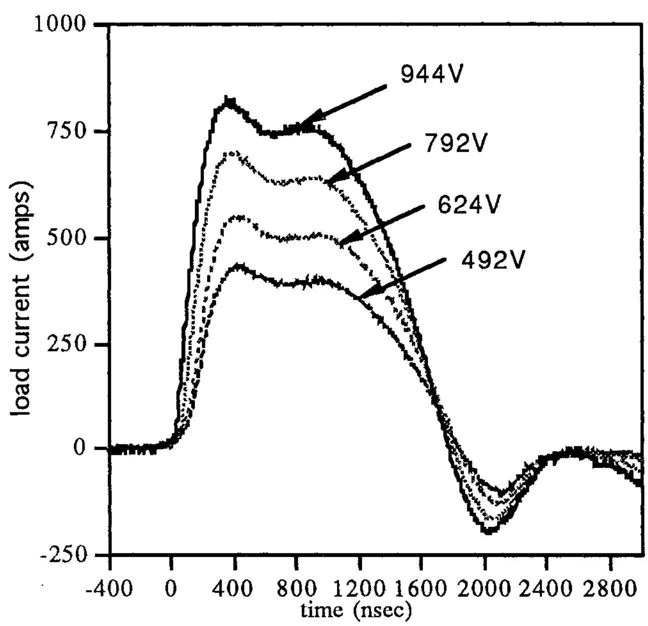


Figure 4. Load current pulse obtained with N-MCT at various PFN bias voltages.

somewhat less peak overshoot. The 10%-90% load current risetime, measured to the peak of the load current pulse was ~220 nsec, averaged over all bias voltages. Measured to the nominal "flat-top" of the load current pulse, the 10%-90% risetime average was ~ 170 nsec. Switching speed increased by ~10% as bias voltage increased from minimum to the maximum of 944V.

At the max. bias of 944V, a peak current of 832A was delivered to the load. This corresponds to a di/dt of 3.8 kA/μsec. Switching efficiency was very good, averaging 88%, indicating low on-state resistance of the MCT.

B. HCT Switching

The HCT 603-45A01 was evaluated at PFN bias voltages up to 3860V. At first, results were very poor, with switching risetimes ~1 μsec. This was found to be due to too slow gate driver pulse, as the gate driver supplied by ABB was not intended for high-speed pulse applications. The gate driver was modified (by reducing lead inductance and replacing capacitors, etc.) until a gate driver pulse with ~100 nsec risetime was obtained. HCT switching then improved, with average 10%-90% risetimes of ~520 nsec. Load current waveforms obtained with the HCT are shown in Figs.5 and 6.

At relatively low bias voltage, as in Fig.5, the switched curent rises in phases, the risetime having a fast and a slow component. This effect decreases with increasing bias and is not noticeable at the maximum applied bias of 3860V. This effect is probably due to some delay in the plasma spread within the device. The step visible in the 480V waveform after the main current pulse is most likely due to mismatch with the load due to increased on-state resistance at low voltage. Note that this effect disappears at higher bias voltage.

At the max. bias of 3860V, a peak current of 2960A was delivered to the load. This corresponds to a di/dt of 5.7 kA/μsec. Switching efficiency, which varied with applied bias, was 77% at max. bias of 3860V, decreasing to 63% at 480V.

Conclusion

The high-speed switching characteristics of the N-MCT and the HCT were investigated in a circuit which mimicked HPM modulator pulse shape requirements. The investigation was only a limited success, as neither device was as fast as hoped, both failing to achieve the circuit-limited risetime of 136 nsec. However, the N-MCT, with a risetime of 220 nsec, was impressive and may

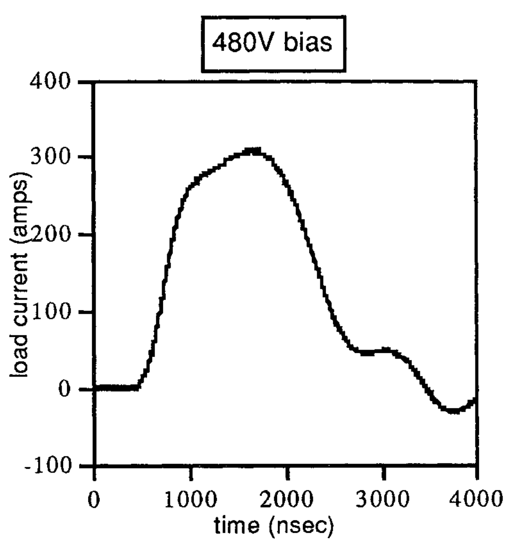


Figure 5. Load current pulse obtained with HCT at 480V PFN bias.

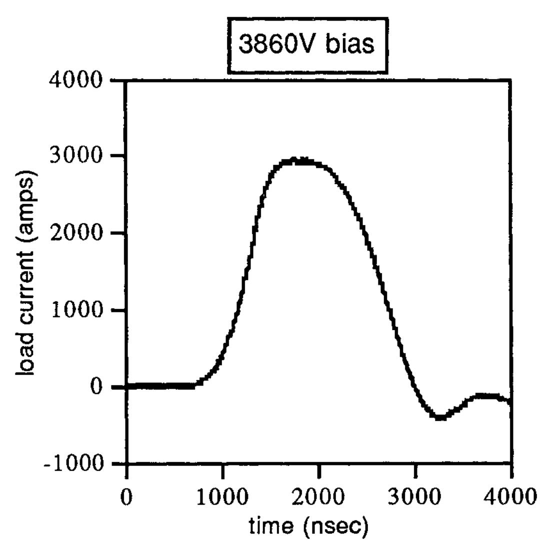


Figure 6. HCT-switched load current pulse at maximum bias of 3860V.

be suitable for some modulator applications, although it may not be appropriate for 1-2 μsec pulsewidth applications. From these tests, the relatively slow HCT is also not suited for 1-2 μsec pulsewidth modulators. Both the N-MCT and the HCT, though, may be appropriate for longer pulse (5-10 μsec) modulators.

Clearly, to make use of solid-state switches in real modulators, the switches will have to be used in series/parallel combinations and operate at high PRF. Future work will focus on investigating pulse switching of series/parallel combinations of devices at higher voltages, up to 25kV, as well as establishing PRF limits. The goal, ultimately, is to produce a solid-state switch demonstrator module operating at 25kV at 1kHz in a typical HPM high-impedance PFN.

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